Rise time of geomagnetic sudden commencements —Statistical analysis of ground geomagnetic data—

T. Araki*, T. Takeuchi, and Y. Araki

Department of Geophysics and Data Analysis Center for Geomagnetism and Spacemagnetism, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

(Received April 25, 2003; Revised December 11, 2003; Accepted January 2, 2003)

The relationship between the rise time, dT, and amplitude, dH, of geomagnetic sudden commencements (SCs) observed on the ground is studied paying special attention to problems of data used in analyses by previous workers and extraction of direct effects of the solar wind interaction with the magnetopause. We measured dT and dH of nighttime SCs recorded on rapid-run magnetograms at a low latitude station, Guam, from 1957 to 1975 and made a scatter plot of dH versus dT. The rise time, dT, for a fixed value of dH scatters widely but the range of the scattering becomes narrower for larger values of dH. The upper envelope of the plot shows a clear inverse relationship between dH and dT but dT does not correlate with dH when dH is small. The amplitude, dH, also shows a clear positive relationship with the gradient dH/dT. We assumed that the rise time is essentially determined by time for an interplanetary shock to sweep geoeffective magnetopause length L for ground detection of the magnetospheric compression and calculated the relationship between dH and dT using the shock relations and an empirical relationship between dH and the dynamic pressure jump of the shock. The scatter plot of dH versus dT is reasonably interpreted if L is taken to be about 30 Re.

Key words: Rise time, sudden commencement, geomagnetic storm, solar wind, magnetosphere, interplanetary shock.

1. Introduction

The geomagnetic sudden commencement (SC) in low latitudes begins with a sudden stepwise increase of the H-component. This is caused by a compression of the magnetosphere when an interplanetary shock or discontinuity collides with the magnetopause. The time interval dT between the onset of the SC and the maximum of the H-component is called the rise time. It ranges 2–10 minutes centered around 4 minutes (Maeda *et al.*, 1962).

Nishida (1966) listed the followings as mechanisms which may determine the SC rise time;

(a) The time taken for the front of the interplanetary shock or discontinuity to sweep the geoeffective distance along the magnetosphere,

(b) The difference in travel time of HM waves to an observing point on the ground from sources distributed over the whole geoeffective magnetopause,

(c) The thickness of the front of the shock or discontinuity in the solar wind,

(d) Inertia of the magnetospheric plasmas against a sudden deformation,

(e) The broadening of the wave front during the passage through the magnetosphere due to multi-reflection.

Dessler *et al.* (1960) tried to explain dT in terms of a combination of the mechanisms (a) and (b) above and calculated a build-up time of SC amplitude as 1–6 min. Yokouchi (1953) analyzed SCs observed at Kakioka (geomag. lat. = 26.9 deg.) for the period 1924–1951 and indicated that the averaged dT shows the diurnal variation with the maximum (about 6 min) at pre-noon hour and minimum (about 2 min) in early morning (around 6 h LT). Ondoh (1963) examined dT of 29 SCs and 16 negative SIs (Sudden Impulses) observed at 5 low and middle latitude stations during the IGY by using rapid-run magnetograms. His results showed that dT of both SCs and negative SIs is shorter in daytime than in nighttime. Assuming that (a) and (b) are the most important mechanisms, he estimated the geoeffective size of the magnetosphere to be 17–26 Re. Fowler and Russell (2001) discussed the rise time based upon the mechanism (a).

Three papers exist which describe the relationship between dT and the SC magnitude dH. Pisharoty and Srivastava (1962, we denote it as paper 1 here) showed an inverse relationship between dT and dH by analyzing 41 SCs observed at Alibag (9.8 deg.) and reported that the result was consistent with the model for dT proposed by Dessler *et al.* (1960). The inverse relationship is also shown statistically by Mayaud (1975, paper 2) but Chapman and Bartels (1962; paper 3) reported no relationship between them (Burlaga, 1972).

The inverse relationship between dT and the mean transmission speed of the interplanetary disturbances relative to

*Present address: 90-4 Okazaki-Hoshouji-cho, Sakyo-ku, Kyoto 606-8333, Japan.

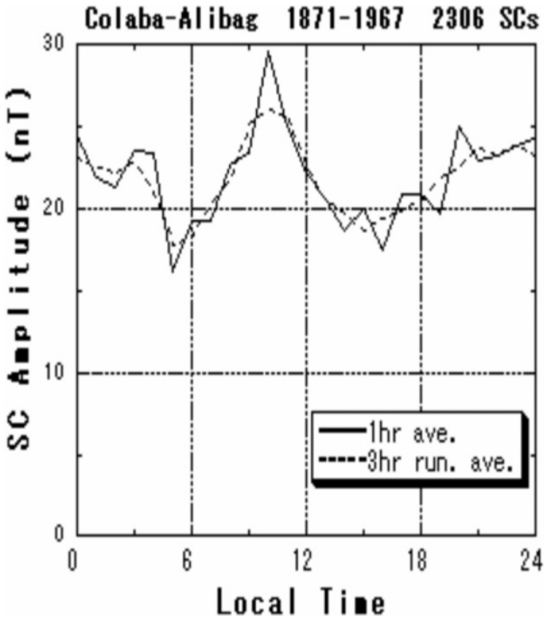

Fig. 1. Local time variation of amplitude of 2306 SCs observed at Alibag (geomag. lat. = 9.8 deg) from 1871 to 1967.

the solar wind from the sun was found by Nishida (1964). He suggested that SCs with dT smaller than 2 minutes can be attributed to interplanetary shocks and SCs with dT larger than 2 minutes to small amplitude waves or tangential discontinuities. He (1964) assumed that dT is principally determined by the mechanism (a) and/or (c) and proposed 20–30 Re as the most probable geoeffective magnetospheric size. Burlaga and Ogilvie (1969) compared 19 worldwide geomagnetic variations and in situ observations of interplanetary disturbances and reported that neither the SCs with long rise time were necessarily due to tangential discontinuities nor those with short rise time were caused by shocks and that the rise time has no relation with velocity of interplanetary disturbances.

The description above about past studies indicates that the rise time of SC has not yet been well understood in both data analysis and theoretical interpretation. It is especially important to confirm which of the two inconsistent analyses for the dH-dT relationship (Pisharoty and Brivastava, 1962; Chapman and Bartels, 1962) is correct. Any hypotheses to interpret the rise time should be consistent with the confirmed dH-dT relationship. If the inverse dH-dT relationship shown by Pisharoty *et al.* is denied, the mechanism (a) above can not be accepted to interpret the rise time.

There are the following problems in the analyses of the above 3 papers on dH-dT relationship

(f) Although the amplitude of SC has a clear LT dependence (for example, Russell *et al.*, 1992), all 3 papers did not consider the effect at all. Here in Fig. 1 we show the LT variation of the amplitude of 2306 SCs observed at Alibag. We see that the amplitude is higher in daytime than nighttime and has two minimums in dawn and dusk. The difference between the peak (29.5 nT) at 10 h LT and the minimum (16.2 nT) at 5 h LT reaches 60% of the averaged value (22.0 nT).

(g) The rise time also depends upon local time, as pointed out by Yokouchi (1953) and Ondoh (1963). It is not taken into consideration in the 3 papers.

(h) Normal-run magnetograms (photographic records) were used in the analyses of papers 2 and 3. Chart speed of the normal-run magnetograms is 20 mm/hour (3 min = 1 mm). The time resolution is not sufficient for accurate measurement of the rise time.

(i) Event number 41 used in the analysis of paper 1 is not enough to obtain reliable statistical results.

(j) Data from "tropical stations" were used in paper 3. It means that the author used mixed data taken from more than 2 stations with different latitude and local time. It degrades quality of the analysis.

Thus we need a new analysis paying special attention to the problems (f)–(j) above in order to check which of the 3 papers is correct and to study other characteristics on relationship between dH and dT.

The global disturbance field of SC observed on the ground is decomposed into three sub-fields as follows (Araki, 1977 and 1994),

$$D_{sc} = DP_{pi} + DL_{mi} + DP_{mi} \tag{1}$$

here subscripts, pi and mi express the preliminary impulse and the main impulse of SC, respectively. The sub-fields DP and DL mean disturbances dominant in the polar and low latitudes, respectively. The H-component variation of the DL-field shows a simple stepwise increase which directly reflects interaction of an interplanetary shock or discontinuity with the magnetopause. The DP-field is produced by electric currents secondary induced in the magnetosphere and the ionosphere and the amplitude and waveform of it greatly depend upon local time and latitude. It is generally larger than the DL-field in high latitudes and the dayside equator and deforms the SC waveform from the simple stepwise increase. We should, therefore, make maximum efforts to extract the pure DL-field by removing the DP-field when we discuss SC in relation with the solar wind dynamic pressure effects. Nobody has paid attention to this point so far.

In this paper, results of an analysis on the dH-dT relationship are shown in which special attention is paid to data problems mentioned by (f)–(j) above and to minimize effects of the DP-field and then a model is presented for interpretation of the results.

2. Data Analysis

Intensity of the DP-field generally decreases with decreasing latitude but it is greatly enhanced in the day side equator (Araki, 1977 and 1994). Therefore, it is best to use data from night side equatorial stations when we study the DL-field. Although the DP-field of SC may appear even in the night side equator (Araki *et al.*, 1985), the effect on the rise time and amplitude would be negligibly small if a sub-storm is not triggered by the SC. Figure 1 indicates that the SC amplitude is not changed much in the nighttime at Alibag. Since data accumulation from high time resolution digital geomagnetic observations near the equator is not yet

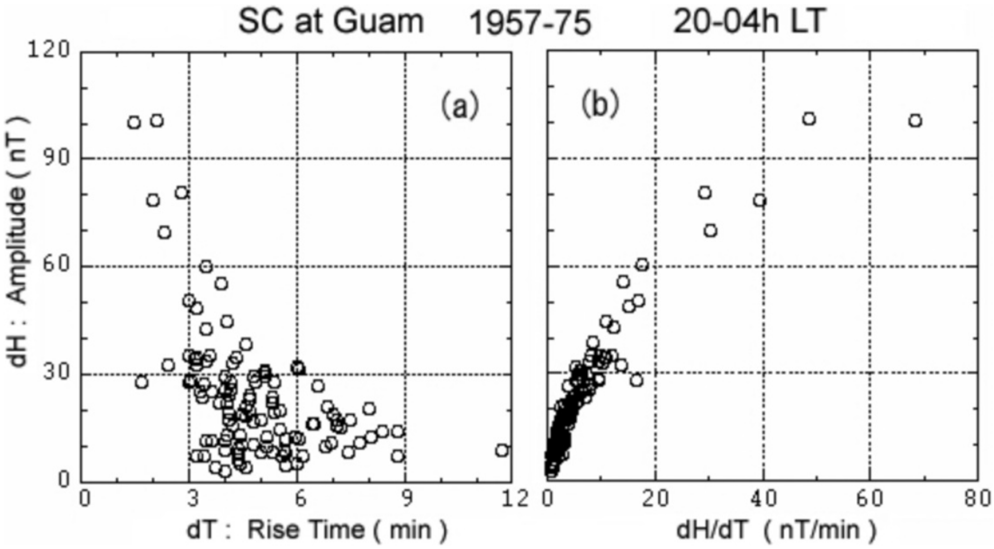

Fig. 2. (a) The amplitude (dH) versus rise time (dT) of SCs observed in nighttime (22 h–04 h LT) at Guam (geomag. lat. = 4.4) for 17.5 years from July, 1957 to December, 1975. (b) The amplitude (dH) versus gradient (dH/dT) of the SCs in Fig. 1(a).

sufficient, we use here analog rapid-run magnetograms of Guam (geomag. lat. = 4.4°) for 18.5 years from July, 1957 to December, 1975. In order to avoid subjectivity of the authors, we selected all the night time (20–04 h LT) SCs listed by Mayaud (1973) for the period 1957 to 1967 and added SCs for the period 1968 to 1975 of which the amplitude is larger than 20 nT in his another list (1977).

Figure 2(a) is a scatter plot of the amplitude, dH versus the rise time, dT of the total 108 SCs analyzed. The maximum H-component amplitude at Guam is 100.8 nT in this period and dT mostly ranges from 1.5 min to 9 min. Scattering of dT is larger for smaller dH but becomes smaller with increasing amplitude. The right upper envelope shows a clear inverse relationship between dH and dT, but dT has no correlation with dH for SCs with small dH. There is a left boundary of scattered data points which decreases rapidly with increasing dT.

By using the same data set we plotted dH versus the gradient dH/dT of SC in Fig. 2(b). A clear positive correlation can be seen between the two quantities. This is consistent with an analysis by Mayaud (1973) but scattering of the data points here is much smaller. It owes to SC selection limited to the night time low latitude and higher time resolution data. We can say “Large amplitude SC increases rapidly”. A similar analysis made by the use of data from Tucson (geomag. lat. = 40.5°) also showed the positive relationship but the data points were more scattered than those in Fig. 2(b). This suggests the contamination of the DP-fields.

3. Interpretation

Here we assume that the rise time of SC is essentially determined by the time necessary for an interplanetary shock to sweep the geoeffective length L of the magnetosphere (mechanism (a) above). Other mechanisms might contribute to the rise time but we consider that the effects are secondary. The geoeffective length here means a distance measured tailward from the sub-solar point beyond which the effect of the interaction between the interplanetary shock and the magnetopause does not propagate to the ground with significant amplitude.

If this assumption is valid, the rise time, dT, is given by

$$dT = L/V_{shock},\ V_{shock} = V_{sw} + M_c \times V_c \tag{2}$$

where V_{shock} is velocity of shock which sweeps the geoeffective magnetospheric length L and V_{sw}, V_c and M_c are the solar wind velocity, characteristic wave velocity and Mach number in the solar wind, respectively.

Roughly speaking, a shock with a higher Mach number has larger jump in the dynamic pressure and sweeps the effective length in shorter time. It might produce, therefore, an SC with shorter rise time and larger amplitude on the ground resulting in an inverse correlation between dH and dT and a positive correlation between dH and dH/dT. The value of dH, however, does not uniquely correspond to the value of dT. Shocks with different Mach number may have the same jump in the dynamic pressure depending upon physical quantities in front of the shock and the same jump in the dynamic pressure may produce different dH on the ground depending upon magnetospheric conditions (for example, the size of the magnetosphere before occurrence of SC). Moreover, dT depends upon the upstream solar wind velocity as shown by Eq. (2).

Now we have an empirical linear relationship between the amplitude of SC (dH) on the ground and the change in square root of the solar wind dynamic pressure P in both sides of an interplanetary shock front or discontinuity (Siscoe *et al.*, 1968),

$$dH = \alpha d(\sqrt{P}) = \alpha(\sqrt{P}_2 - \sqrt{P}_1),\ P = \rho V^2. \tag{3}$$

Here, ρ, V and α are density and velocity of the solar wind and a proportional coefficient, respectively. Subscripts, 1 and 2, specify quantities in front of and behind the shock front or discontinuity, respectively.

If the Mach number and physical quantities in front of the interplanetary shock are given, density ρ and velocity

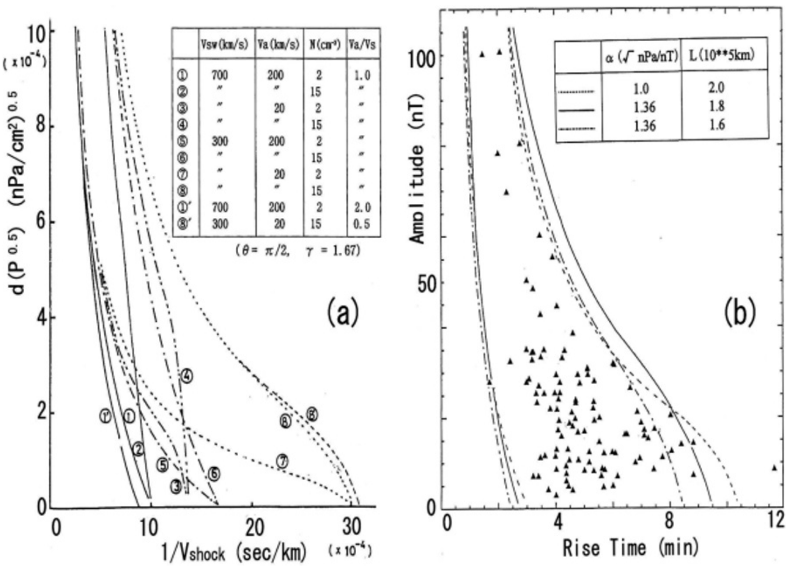

Fig. 3. (a) The relation between the change in the square root of the dynamic pressure of the interplanetary shock and the inverse of the shock speed. (b) Plots of amplitude versus rise time of the observed SCs (same as Fig. 1(a)) together with calculated outermost curves for 3 combinations of assumed parameters, α and L.

V behind the shock can be determined by using the shock relations and consequently $d(\sqrt{P})$ is specified. Then the corresponding dH is determined by using the coefficient α experimentally proposed (see, Araki *et al.*, 1993). At the same time dT can be calculated by Eq. (2) for the given set of the solar wind parameters.

Figure 3(a) shows the result of the calculation on the relation between $1/V_{shock}$ and $d(\sqrt{P})$. The solar wind speed, Alfven speed and mass density in front of the shock vary 300 km/sec to 700 km/sec, 20 km/sec to 200 km/sec and 2 cm^{-3} to 15 cm^{-3}, respectively. The ratio of Alfven speed to the acoustic speed is assumed to be unity for most of the cases (for curves 1 to 8). This ratio does not change the result much as seen from curves $1'$ and $8'$ for which the ratio is taken to be 2 and 0.5, respectively. Here θ (angle of velocity to magnetic field) and γ (specific heat ratio) are assumed to be 90° and 1.67, respectively. One particular curve in Fig. 3(a) is obtained by changing Mc for a fixed set of the solar wind parameters.

If the values of α and L are specified, we can convert the ordinate and abscissa of Fig. 3(a) to the amplitude, dH and rise time, dT. The results are given in Fig. 3(b). Here we took 3 sets of combination of α and L and plotted curves corresponding to the outermost curves $1'$ and $8'$ which bound the region of possible combinations of $1/V_{shock}$ and $d(\sqrt{P})$ in Fig. 3(a). Observed dH and dT in Fig. 2(a) are also plotted in Fig. 3(b).

All data points except a rightmost one in the figure distribute between the two outermost curves corresponding to parameters $\alpha = 1.0$ (nPa)$^{0.5}$nT and $L = 2 \times 10^5$ km (about 30 Re). So we can say that the compression along approximately 30 Re from the sub-solar point of the magnetopause effectively produces SC on the ground.

4. Discussions

The Figure 2(a) provides the most accurate dH-dT relationship which can be actually obtained with presently available data. The accuracy was achieved by studying *a larger number* (108) of SCs recorded on *nighttime rapid-run magnetograms* at *a fixed low latitude* station (Guam). The averaged dH curve is not indicated because we consider that each data point is physically meaningful and that the averaged dH has not significant physical meaning. We have to explain the physical meaning of the data point distribution and the two boundaries of the distribution in this figure. The previous 3 papers just showed the averaged dH versus dT and the range of the data distribution was indicated by the error bars. It means that the averaged dH curve is physically meaningful but deviations from the averaged dH are just errors. When an SC with abnormally large dH and/or abnormally small dT is observed, we can check the abnormality by plotting it in this figure. It is impossible in the previous 3 papers because the deviation from the averaged values is considered to be an error there.

Equation (2) applies to propagating interplanetary shocks. Now we know that interplanetary discontinuities also produce SCs. Because discontinuities propagate with solar wind speed which has no relation with the dynamic pressure jump, we lose a clue to study relationships between dH and dT of SCs caused by the interplanetary discontinuities. In Fig. 2(a) we found that dT scatters much for small amplitude SCs. It might be due to higher probability of SCs produced by the discontinuities. Small amplitude SCs may be produced also by weak shocks, however. We should investigate further, using satellite data, what causes large scattering of dT when dH is small.

Although we have obtained about 30 Re as the geoeffective length L for magnetospheric compression due to interplanetary shocks, this is, of course, the most probable length and it will change in case by case. When the shock is stronger, L will be longer because the compression of the more distant tail magnetopause may affect ground observations. However, the sweeping velocity of the shock will be faster for stronger shock and effects for the rise time will be cancelled out.

Difference in propagation time from the sub-solar point and the tail-ward edge of the geoeffective magnetopause length (mechanism (b) above) will also contribute to the rise time. If we take the difference in the propagation path length as 10 Re and the averaged propagation speed as 600 km/s (Araki, 1994), the time difference becomes about 100 sec. Therefore the mechanism (b) will play more important role for shorter rise time SCs.

Figure 2(a) shows that the rise time measured in the night-time at Guam ranges between 1.5 min and 9 min. This range corresponds to the sweeping shock velocity between 2100 km/s and 350 km/s if we take $L = 30$ Re. It is said that the maximum solar wind velocity ever observed is about 2000 km/s or more for an SC event of August 4, 1972 (Cliver *et al.*, 1990). We checked the rapid-run magnetogram at Guam and scaled the rise time of this SC as 62 sec. Although we have to take local time (6 h 54 m) at Guam into consideration, this short rise time corresponds to an extremely high shock velocity, 30 Re/62 sec = 3080 km/sec. If such a high speed is unrealistic, we have to search for other mechanisms for extreme cases in addition to the mechanism (a) above.

From our experience of long term SC analyses we know that the waveform of SCs in low latitudes is not stepwise but more impulsive when the amplitude extremely large and rise time is extremely short. This suggests that the dynamic pressure change associated with the source interplanetary shock will be impulsive. Therefore we have to consider magnetospheric interaction with a short duration impulsive shock. It will be greatly different from interaction with the stepwise shock considered here. Satellite data analysis is in progress to check the ground data analysis presented here and the impulsive shock interaction with the magnetosphere.

Recently Takeuchi *et al.* (2002) found an SC with unusually long rise time (more than 30 min) on the ground produced by an interplanetary shock with a normal sharp rise. It was confirmed that the shock normal deviated much from the sun-earth line so that the interaction time between the shock and the magnetopause becomes longer. We should add “inclination of the interplanetary shock or discontinuity” as an important factor responsible for the rise time of SC.

When the interpretation of the SC rise time is once established, it will contribute to knowledge of solar wind conditions in the pre-satellite era.

Acknowledgments. Geomagnetic data used in this analysis were provided by the WDC for Geomagnetism, Kyoto, Graduate School of Science, Kyoto University.

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T. Araki (e-mail: arakit@obsc.mbox.media.kyoto-u.ac.jp), T. Takeuchi, and Y. Araki